Airborne Required Time of Arrival (RTA) Control and Integration with ATM

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Outline

- Motivation
- Single Waypoint RTA
- Multiple Waypoint RTA
- 4D Trajectory Negotiation

Motivation for Airborne Time-based Speed Control

- **Many concepts for ATM Automation include Trajectory Based Operations, based on time.**

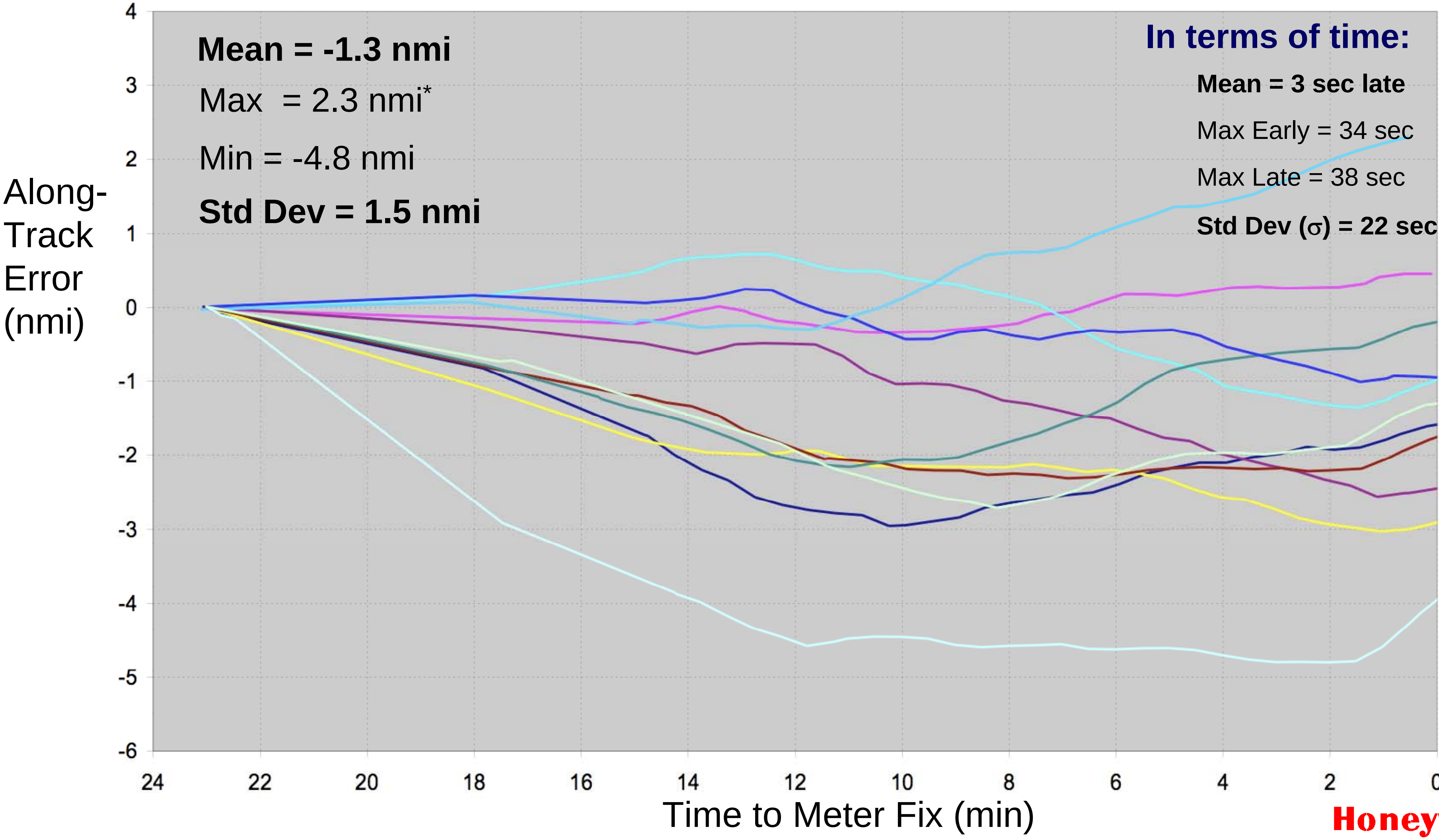
- **There are fundamental limits to accuracy using ground-based speed control to achieve time-based operations.**
  - **Typical concept is use FMS for 3D path with speed clearances from ground**
  - **Measurement of aircraft state**
    - Radar accuracy limits
    - Time delays on measurements
  - **Modeling of aircraft performance is generic to type**
    - dash models, engine types, derate settings, etc. are missing
  - **Control actuation limitations**
    - Inherent time-delays from measurement of disturbance to control action by pilot
  - **Controller workload**
    - Frequency of clearances by controller are limited by workload

- **Airborne feedback control of speed to track time objectives can drastically reduce the trajectory dispersion.**

Example from Tailored Arrivals results

Enroute Descent Advisor – Along Track Prediction Accuracy - 23 min time horizon

Acknowledgement: from Rich Coppenbarger, NASA Ames Research Center



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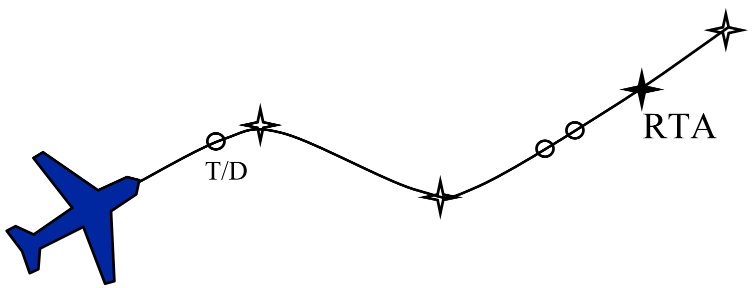
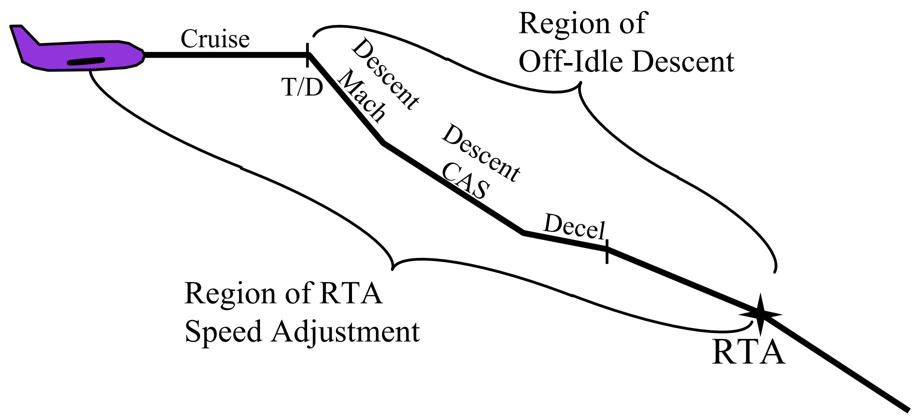
Time-based Aircraft Control - RTA

- **Onboard speed adjustment to meet waypoint time-of-arrival constraints**
- **Based on trajectory predictions function in Flight Management System**
- **Periodic recalculation of ETA and adjustment of airspeed commands.**
  - **Off Idle descent planned to allow for automatic throttle changes**
  - **Prior to Top-of-Descent, the T/D point may move with descent speed changes.**
  - **When in descent, path is frozen but speed command updated to meet the RTA.**
  - **If throttle hits idle, pilot must add drag to maintain path and speed.**





Basic RTA Algorithm

- Consider a simplification of the FMS Trajectory Predictor

$$ETA = \sum_{wpts} \frac{\mathrm{LegDist}}{\mathrm{GndSpd}} + Current\_Time$$

- Speed profile hooked to a speed adjustment parameter (SAP), "speed control knob"
  - For example,

$$Spd\_cmd_i = Spd\_default_i * (1 + SAP * gain_i)$$

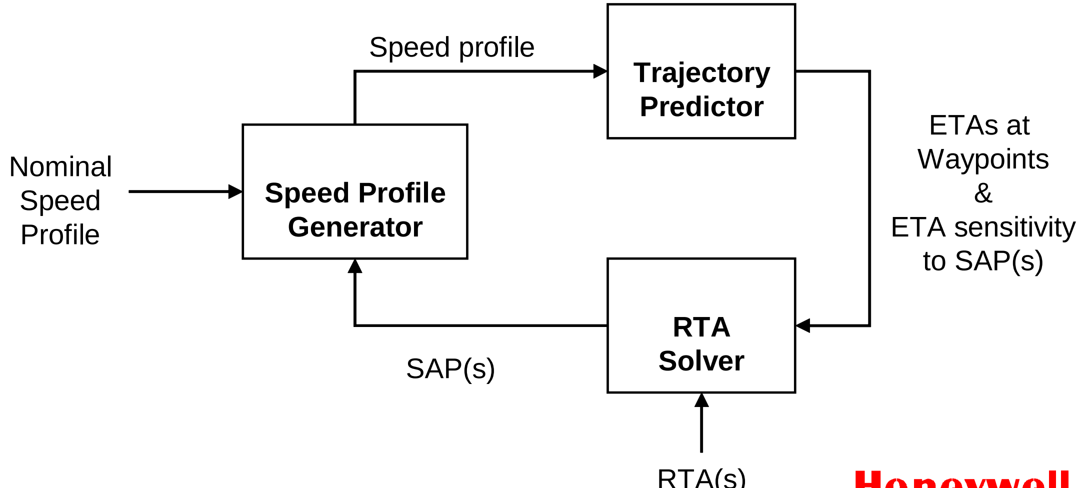
$$\text{where}, i \in \text{climb\_cas}, \text{climb\_mach}, \text{cruise\_mach}, \text{des\_mach}, \text{des\_cas}, \text{etc.}$$

- Differentiating the first equation w.r.t. SAP produces

$$\frac{\partial ETA}{\partial SAP} = \sum \frac{-\mathrm{LegTime}}{\mathrm{GndSpd}} \frac{\partial \mathrm{GndSpd}}{\partial SAP}$$

- This sensitivity is used to estimate a speed adjustment to null the time error.
  - SAP computed iteratively by observing time error on each pass of trajectory predictions.

$$\Delta SAP = \frac{RTA - ETA}{\frac{\partial ETA}{\partial SAP}}$$



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Enhanced RTA Algorithm

- **Non-linearities in the models affect convergence of the algorithm**
  - **primary issue is the effect of speed limits near minimum and maximum speed**
  - **Second order partial derivative accounts for nonlinearities**

$$\frac{\delta^2 ETA}{\delta SAP^2} = \sum_{WPTS}\left[\frac{2\,LegDist}{GndSpd^3}\left(\frac{\delta GndSpd}{\delta SAP}\right)^2 - \frac{LegDist}{GndSpd^2}\frac{\delta^2 GndSpd}{\delta SAP^2}\right]$$

  - **Solution for speed profile requires a quadratic equation**

$$\frac{1}{2}\frac{\delta^2 ETA}{\delta SAP^2}\Delta SAP^2 + \frac{\delta ETA}{\delta SAP}\Delta SAP + TimeError = 0$$

  - **This algorithm converges more quickly than the 1st order algorithm**

Ref: US Patent 6,507,782, “Aircraft Control System For Reaching A Waypoint At A Required Time Of Arrival”, 2003

Preliminary Lab Testing Results

- **Tested this RTA system in two of Honeywell's hardware-in-the-loop validation facility (VALFAC) labs (757 and Gulfstream IV)**

- **Introduced unmodeled disturbances to observe system reaction**
  - **Wind prediction error**
    - 20 knot headwind error
    - 10 knot tailwind error
  - **Effect of turn radius changes with speed**
  - **Changes to RTA while in descent**
  - **Unplanned level-off during descent due to traffic**
  - **Modified vertical constraint while in descent**

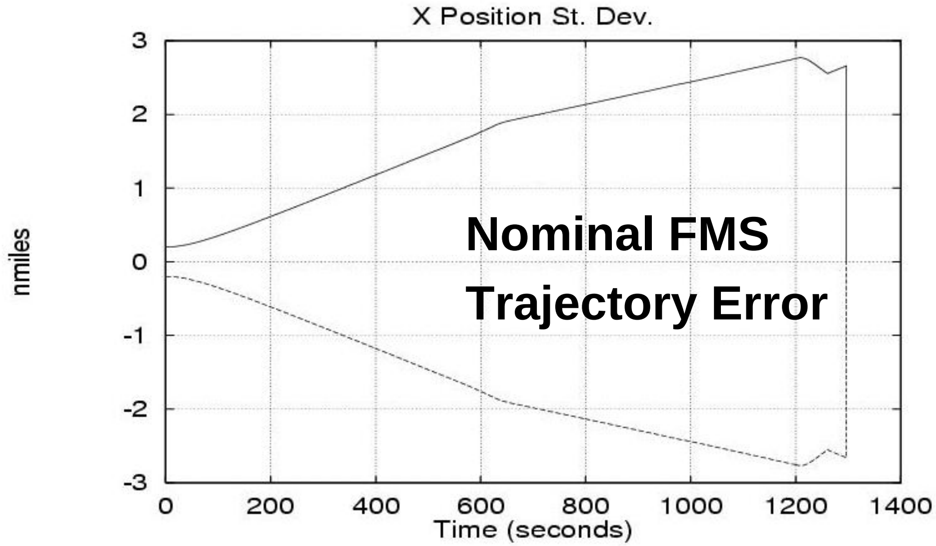
- **In all cases the aircraft crossed the fix within +/- 6 seconds of the RTA**

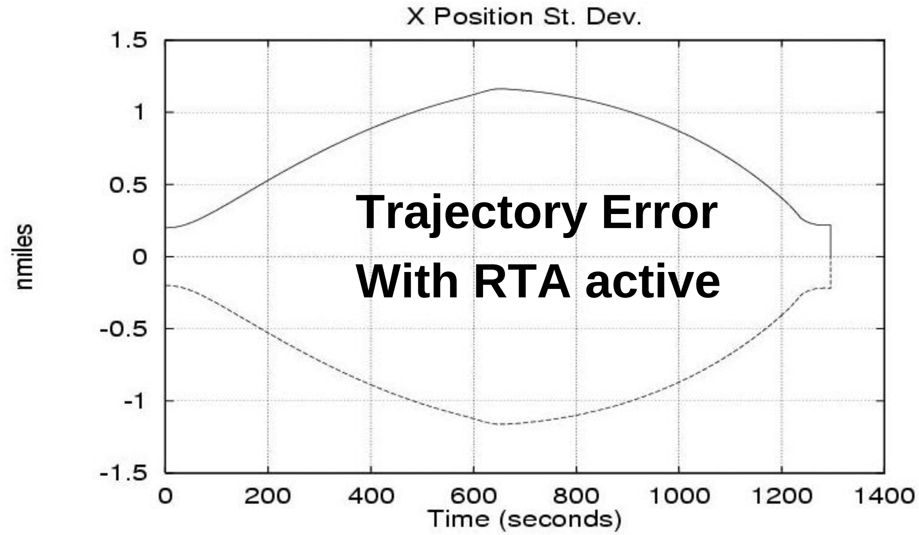
- **Caveat – this was limited testing of a prototype system, not a fully certified system.**

Linear Analysis Results

Ref: "Sensitivity of Trajectory Prediction in Air Traffic Management and Flight Management Systems", Michael R. C. Jackson, Ph.D. Thesis, University of Minnesota, Dec 1997.

- **RTA Reduces Trajectory Error**
  - **Nominal FMS trajectory sensitivity shown with a given set of disturbances**
    - Very similar results to Tailored Arrivals
    - My error sources appear to be about 50% worse (2.6 mile vs. 1.5 mile St Dev)
  - **RTA control reduces trajectory sensitivity most dramatically at end, but also through whole trajectory.**
- **Conclusion: ATM system doesn't need to worry about FMS RTA speed maneuvers causing problems – resulting trajectory better matches the one used in conflict probe than "open-loop" FMS trajectory.**





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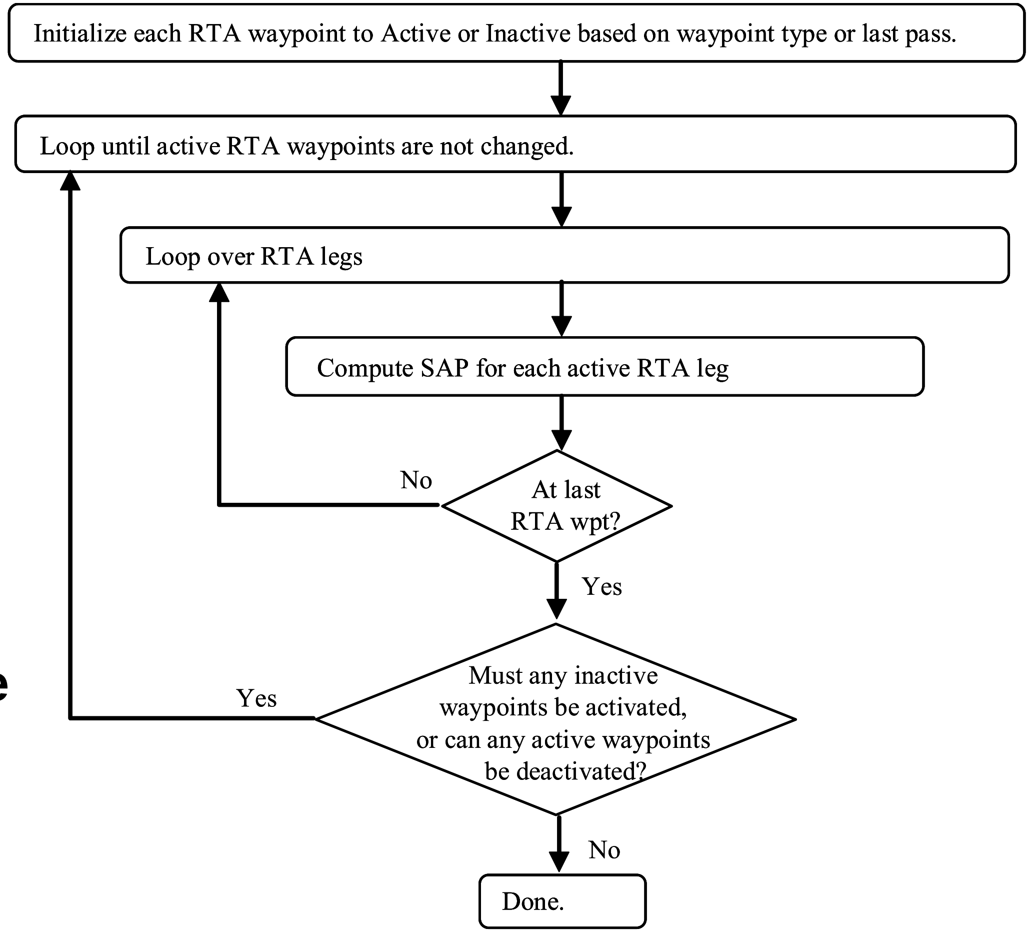
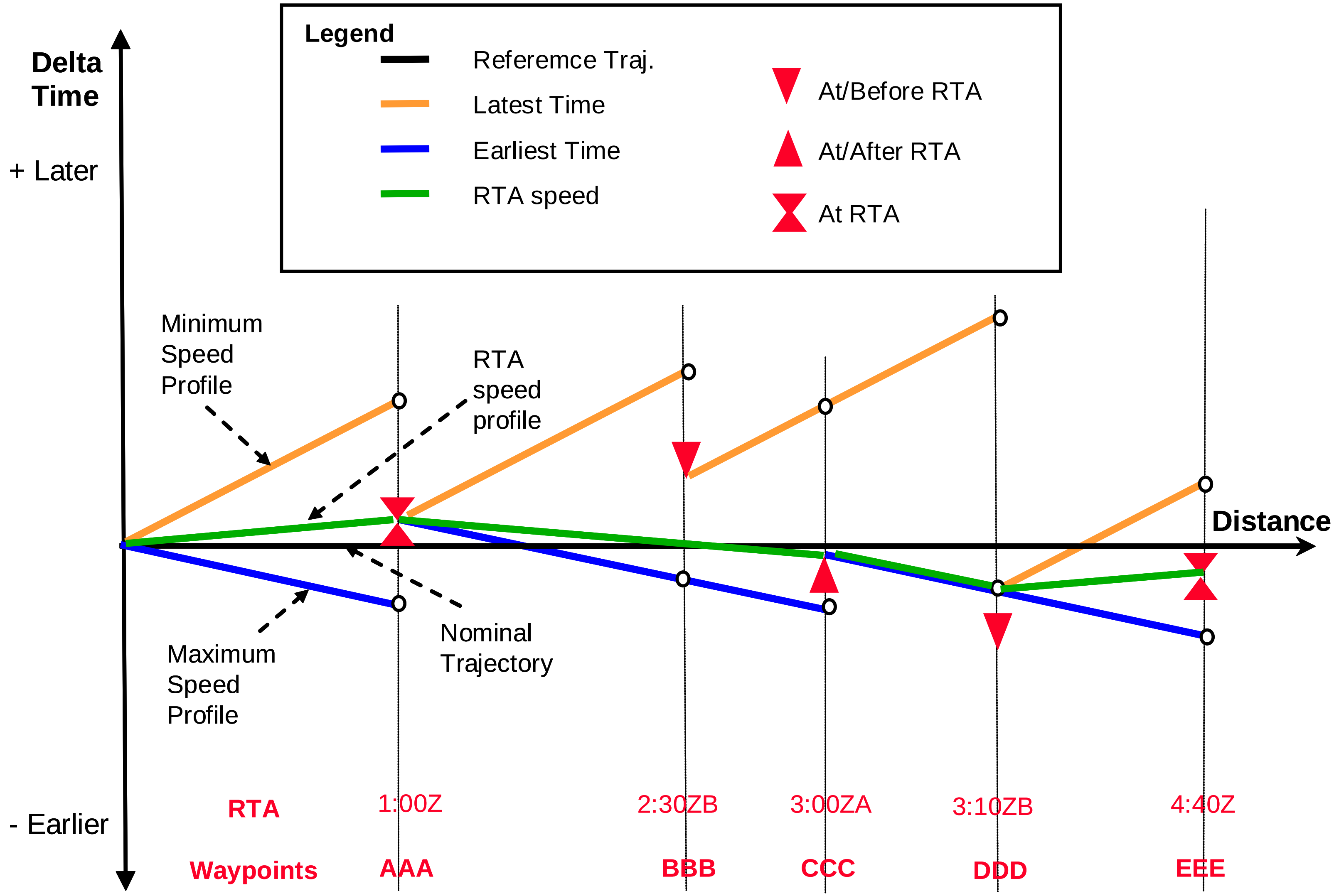
Multiple Waypoint RTA

- **Single waypoint RTA may leave open too much uncertainty for some ATM concepts**
- **Multiple waypoint RTA allows ATM to specify multiple time constraints**
  - **Each RTA can be**
    - AT constraint
    - AT/Before
    - AT/After
- **FMS can solve this as a sequence of single waypoint RTAs**
  - **Earlier RTAs have priority if they cannot all be achieved**

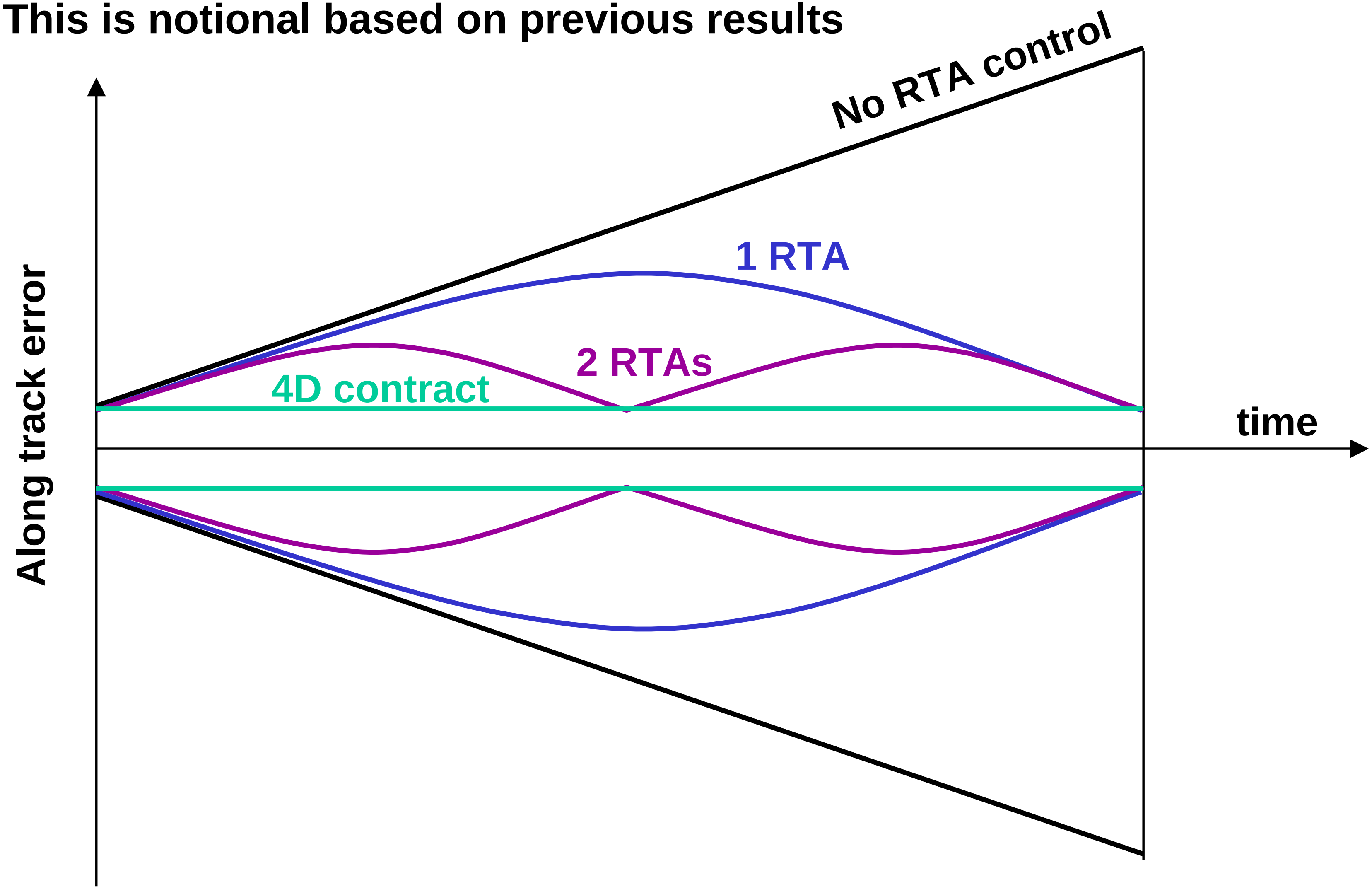


Multiple Waypoint RTA Example



Multiple RTA Effect on Uncertainty

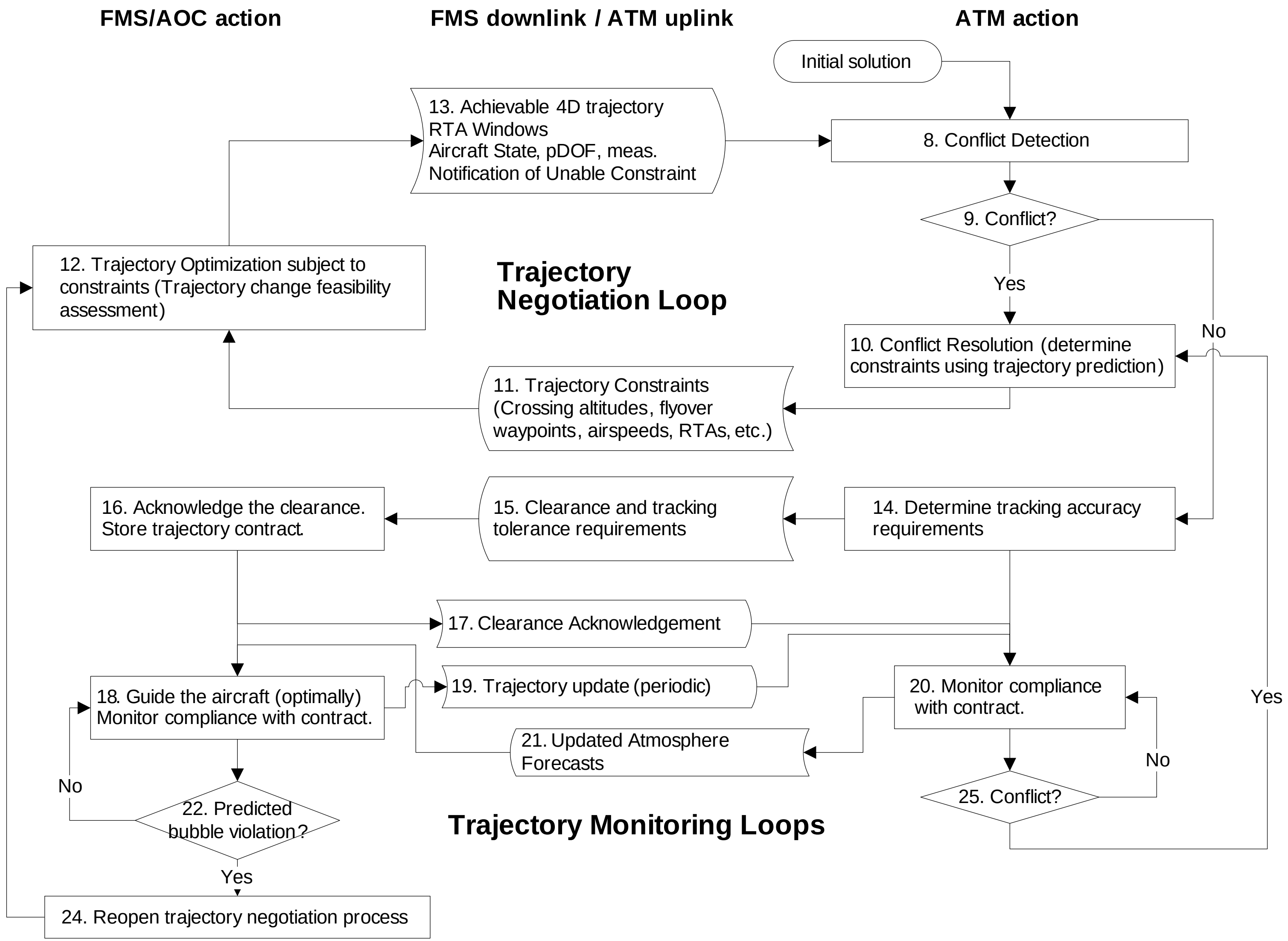
- This is notional based on previous results



Air/Ground Trajectory Negotiation

- **4-D trajectory tracking can further improve predictability of flight.**
  - **FMS actively tracks the trajectory used in ATM's conflict probe**
- **Trajectory negotiated between controller and pilot using automation**
  - **ATM uplinks trajectory constraints (waypoints and RTAs)**
  - **FMS generates a compliant trajectory (using RTA capability) and downlinks it**
  - **ATM performs conflict probe and issues clearance**
  - **FMS uses feedback to track the predicted trajectory**
    - Can request new clearance if/when the trajectory is no longer optimal or feasible
- **Trajectory generation need on ground and airborne**
  - **Ground system required for unequipped aircraft and to iterate on solution**
  - **Airborne system required to assure trajectory is feasible to fly and to improve fuel efficiency**
- **Data exchange (via ADS-B & FIS-B) increases accuracy of both ground and airborne trajectory prediction systems.**

Air/Ground Trajectory Negotiation - detail



Acknowledgement – this work was done with Seagull Technologies (now Sensis) on the NASA VAMS Point-to-Point Project

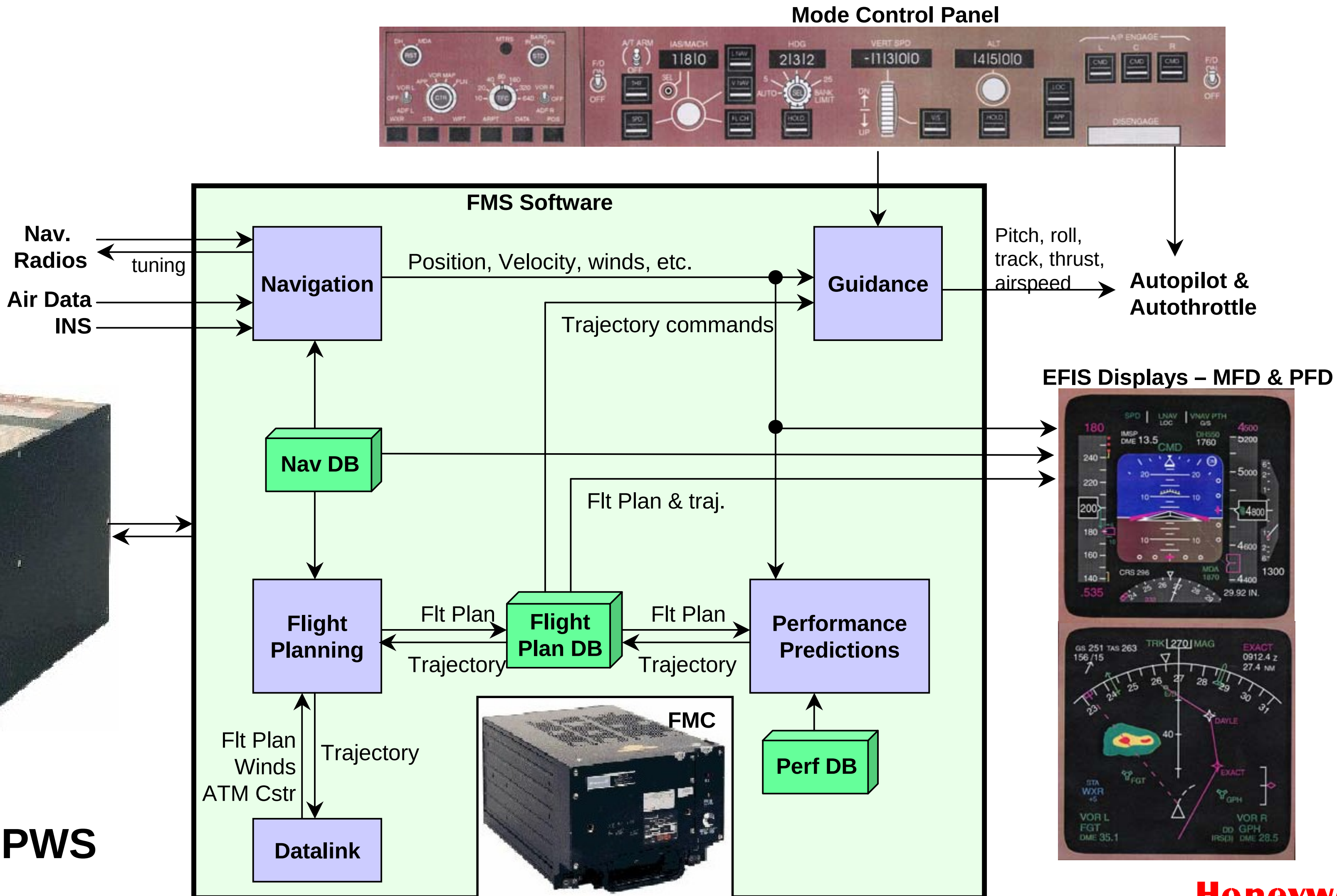
Summary

- **Airborne FMS control to time in terminal area is feasible**
  - **But, we only recommend applying time constraints as needed to solve ATM problems**
    - **Single RTA** may solve majority of issues
    - **Multiple RTA** may be required for crossing traffic situations or airspace boundaries
    - **4D trajectory negotiation** may provide additional information to ATM for high density ops
- **Benefits**
  - **Improved accuracy and predictability of trajectories**
  - **Reduced controller workload**
    - No need for several speed clearances to achieve arrival time – FMS generates internally
  - **Helps enable Continuous Descent Approach & Tailored Arrivals**
    - Reduced fuel burn and emissions
    - Reduced noise
    - Reduced flight time delay
- **Challenges**
  - **Shared separation responsibility between ATM & pilot**
    - Requires ATM tools & culture shift
  - **Mixed equipage issues**
  - **Chicken & Egg problem: ATM system <> Airplane Capability <> Airline Investment …**

Questions?

Modern aircraft have capable control systems

Flight Management Systems accurately measure, model, and control flight



Also:
TCAS, EGPWS

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